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*Applied Ocean Physics and Engineering Department*

June 20, 2014

Dr. Robert H. Headrick
Office of Naval Research, Code 322
875 N. Randolph Street
Arlington, VA 22203-1995

Dear Dr. Headrick:

Enclosed is the Final Report for ONR Grant No. N00014-10-1-0646 entitled "Continued Analysis of High-Frequency Broadband Acoustic Scattering from Non-Linear Internal Waves During SW06," Principal Investigator, Dr. Andone Lavery.

Sincerely,

Shirley Barkley

Shirley Barkley
Administrative Associate II

Enclosure

cc: Administrative Grants Officer
Defense Technical Information Center
Naval Research Laboratory
Grant and Contract Services (WHOI)
AOPE Department Office (WHOI)

MS#12 • Woods Hole, MA 02543 • 508.289.2727 • Fax 508.457.2194

# Continued Analysis of High-Frequency Broadband Acoustic Scattering from Non-Linear Internal Waves during SW06

Andone C. Lavery
Department of Applied Ocean Physics and Engineering
Woods Hole Oceanographic Institution
Bigelow 211, MS #11, Woods Hole, MA 02543
telephone: (508) 289-2345 fax: (508) 457-2194 email: alavery@whoi.edu

Award Number: N00014-10-1-0646
http://www.whoi.edu/people/alavery

## LONG-TERM GOALS

To understand high-frequency broadband acoustic backscattering from small-scale physical processes, such as internal waves, turbulence, and microstructure, in shallow, stratified waters.

## OBJECTIVES

The primary objective of the overall research program was to measure high-frequency broadband acoustic backscattering in highly stratified, energetic environments and to determine the contribution to scattering from temperature and salinity microstructure relative to other scattering sources. Testing the validity of existing scattering models and the initial development of new, and/or extensions of existing, simple physics-based scattering models was a secondary objective of this work.

To accomplish the stated objectives, high-frequency broadband (150-600 kHz) acoustic backscattering measurements were performed during the generation, propagation, and dissipation of non-linear internal waves in August 2006 as a part of the SW06/NLIWI experiment. Almost coincident microstructure measurements were collected by Jim Moum with a profiling microstructure instrument, Chameleon. The contribution to scattering from biological organisms was quantified using net-samples, from which the zooplankton taxa, size, and depth (in coarse vertical bins) can be determined.

## APPROACH

Over the last 40 years, there has been significant research effort directed at using high-frequency acoustic scattering techniques to remotely investigate the distribution, abundance, and size of marine organisms (Simmonds and MacLennan, 2005, and references therein). In fact, some of the world's largest stocks of zooplankton, such as Antarctic Krill (Nicol and Endo, 1999), as well as large fish stocks, are assessed using single or multi-frequency narrowband acoustic scattering techniques (Simmonds and MacLennan, 2005). More recently, there has also been significant

effort directed towards the quantitative use of narrowband acoustic scattering techniques for investigating small-scale physical processes, such as oceanic microstructure (e.g. Goodman, 1990; Seim et al., 1995; Lavery et al., 2003; Ross and Lueck, 2003; Warren et al., 2003). Acoustic scattering techniques provide a rapid, high-resolution, synoptic, remote sensing alternative to more traditional sampling strategies. Yet reducing the ambiguities in the quantitative interpretation of the acoustic returns, with the ultimate goal of accurate, remote classification and quantification of physical (and/or biological) scattering sources, remains one of the outstanding challenges.

In principle, measurements of high-frequency acoustic scattering from oceanic microstructure and zooplankton across a broad range of frequencies, spanning multiple octaves of bandwidth, can reduce the ambiguities typically associated to the interpretation of acoustic scattering at a single frequency or a limited number of discrete narrowband frequencies. The goal is to capitalize on the different characteristic frequency-dependent spectra associated to different scattering sources. The potential for this technique is supported by broadband measurements on caged aggregations of fish (e.g. Simmonds and Armstrong, 1990; Simmonds *et al.,* 1996), free-swimming individual fish (e.g. Lundgren and Nielsen, 2008), and numerous broadband laboratory measurements of fish (e.g. Reeder *et al,* 2004; Au and Benoit-Bird, 2008), squid (e.g. Lee *et al.*, 2009), zooplankton (e.g. Roberts and Jaffe, 2008), and different types of microstructure (e.g. Goodman and Oeschger, 2003; Lavery and Ross, 2007), as well as the fact that many toothed whales use broadband echolocation signals to detect and classify their prey (Au *et al.,* 2009).

There are only a few commercially available (Ross and Lawson, 2009: 85–155 kHz, slightly less than octave bandwidth), or custom-built prototype (Foote *et al.*, 2005: 25 kHz to 3.2 MHz using seven octave bandwidth transducers), high-frequency broadband acoustic backscattering systems that have been used for studying zooplankton and/or microstructure in the field. In contrast, lower-frequency broadband scattering measurements (< 120 kHz) to remotely characterize fish have been performed more prevalently (e.g. Zakharia et al., 1996; Stanton *et al.*, 2010), including measurements involving explosives (e.g. Holliday, 1972; Thompson and Love, 1996; Nero *et al.,* 1998; Love *et al.*, 2004).

The broadband system developed for this project was used to measure high-frequency broadband acoustic backscattering from microstructure and zooplankton in the presence of surface trapped nonlinear internal waves of depression propagating over the New Jersey continental shelf. The frequency range used in this study encompasses many of the narrowband acoustic frequencies typically used to survey zooplankton and turbulent oceanic microstructure, and includes the Rayleigh-to-geometric scattering transition of some typical zooplankton and the diffusive roll-off in the spectrum for scattering from turbulent temperature microstructure for a range of dissipation rates. Almost coincident direct microstructure measurements were performed. Zooplankton community structure was characterized using depth-resolved net-sampling techniques. Some marine organisms, predominantly small fish and zooplankton, can act as passive tracers of physical processes such as internal waves and turbulence, and are a significant confounding factor during the interpretation of high-frequency acoustic volume backscattering. The combination of these data is necessary for the accurate interpretation of the acoustic scattering measurements and, in particular, to determine the relative contribution to scattering from zooplankton and turbulent microstructure. Surface trapped nonlinear internal solitary waves of depression are a unique

feature of coastal oceans and provide a good environment to assess the contribution to scattering from oceanic microstructure as they are both intensely turbulent (Moum *et al.,* 2003) and at sufficiently close range that they generate high signal levels well within the range of surface-deployed, high-frequency broadband acoustic scattering systems. Surface trapped nonlinear internal waves of depression are thought to be generated in the vicinity of the continental shelf break due to the interaction of internal tides with stratified fluid over sharp topography. They then propagate across the continental shelf until they dissipate in shallower waters. Not all the internal wave energy is dissipated in shallow waters, as some is dissipated by the generation of turbulence along the propagation path. Mechanisms for this dissipation of energy are discussed by Moum *et al.* (2003). It is hoped that quantification of broadband acoustic scattering from microstructure generated by these internal waves may contribute to understanding these dissipation mechanisms.

The data analysis involves capitalizing on the broadband nature of the transmitted signals and using pulse compression techniques (Chu and Stanton, 1998; Stanton and Chu, 2008) to both increase the signal-to-noise ratio and the spatial resolution of the measurements. It has been possible to obtain almost cm scale resolution in the direction of acoustic propagation using these techniques, a significant improvement over traditional single-frequency echosounder observations of water-column scattering. Additional information is obtained by further capitalizing on the broadband nature of the acoustic signals by using the spectral content of the scattering to determine if the scattering is consistent with scattering from small-scale fluid processes or biology. In regions in which the scattering is determined to be dominated by turbulent microstructure, existing scattering models have been used to extract parameters such as the dissipation rate of turbulent kinetic energy (see results section below).

## WORK COMPLETED AND RESULTS

*Instrument development and calibration:* A 4-channel high-frequency broadband acoustic backscattering system has been developed spanning the frequency range, in four almost overlapping bins, from 150 kHz to 590 kHz with similar acoustic scattering volumes. The system is designed to either profile with the transducers in a side-looking mode or to be suspended at a particular depth with down-looking transducers (resembling a more traditional echosounder). A SeaBird SBE 49 FastCAT CTD (16 Hz sampling rate) is mounted on the system to measure fine-scale temperature and salinity gradients while in profiling mode. Pitch, roll, and heading are also measured. GPS data are recorded to allow accurate synchronization with other instruments. The system has been calibrated, including measurements of beam patterns, in sea-water tanks at WHOI and at SMAST (on multiple occasions), in the WHOI sea well (also on multiple occasions), and in-situ, using 20 mm and 38.01 mm diameter Tungsten Carbide standard targets

*Field measurements:* This system has been deployed during the SW06/NLIWI experiment during a month long cruise (July 30- August 28, 2006) on the RV Oceanus. Direct microstructure measurements were performed by Jim Moum using the turbulence profiler Chameleon (Moum et al., 1995). The broadband acoustic system was fully operational throughout the experiment and high-frequency broadband acoustic backscattering has been measured for 28 internal solitary wave trains, in some cases chased over many kilometers from generation to dissipation stages. The acoustic system was deployed in both down-looking and side-looking mode, allowing scattering

anisotropy during the passage of internal solitary waves to be investigated. In addition, 5 depth-resolved net tows (MOCNESS) were performed during this experiment in order to quantify biological scatterers.

*High-resolution imaging of small-scale physical processes:* Broadband acoustic scattering measurements enable the use pulse compression signal processing techniques to obtain very high resolution images of many nonlinear internal waves. In combination with the high ping rate (1 Hz), these techniques have allowed fine scale physical processes, such as Kelvin-Helmholtz shear instabilities, typically not well resolved by the direct microstructure measurements, to be imaged at very high resolution (Lavery et al., 2010a,b). Though the direct microstructure measurements provide very high resolution measurements in the vertical, the profiles are relatively sparse (one profile every 2-4 minutes) relative to the acoustic measurements or the spatial scales of the KH instabilities.

*Analysis of direct microstructure measurements and the forward problem based on these data:* Jim Moum and colleagues have completed the analysis of the microstructure measurements collected during the field experiment. These data have been used with existing scattering models (Lavery et al., 2003) to predict scattering from microstructure, and to assess the importance of salinity versus temperature microstructure. These models and microstructure data predict that the scattering from microstructure is dominated by temperature and not salinity microstructure, as would be expected based on the temperature and salinity gradients (Lavery et al., 2010 a,b).

*Analysis of biological samples and the forward problem based on these data:* All the MOCENSS tows performed on the continental shelf during the SW06 experiment have been analyzed (MOCs 2-5) for composition, size, and abundance of zooplankton. The results show that, in general, biomass and numerical abundance of zooplankton are dominated by copepods, with larger copepods located in a deep scattering layer and the shallower waters being populated by smaller copepods. All tows were performed during day light hours. Scattering predictions (the "forward problem") based on these data and available zooplankton models (Lavery et al., 2007) have shown that the predicted scattering from zooplankton is dominated by copepods, amphipods, and pteropods, depending on the frequency, depth, and location (Lavery et al., 2010).

*Scattering due to small-scale physical processes versus biology:* Though the frequency response of the scattering was often consistent with scattering from small zooplankton (scattering increasing with increasing frequency), some regions have been found in which the scattered frequency spectra are indicative of scattering from physical processes. Specifically, scattering spectra from Kelvin-Helmholtz shear instabilities associated with many NLIW were frequently consistent with scattering from microstructure alone (scattering decreases with increasing frequency). Two manuscripts have resulted from this work (Lavery et al., 2010a,b).

*Inversion of broadband spectra for biological and physical parameters:* Simple least squares inversions of the broadband scattering data have been performed at locations in which the scattering spectra are consistent with scattering from small zooplankton alone, and consistent with scattering from microstructure alone. These inversions rely heavily on existing scattering models. For zooplankton, a single scattering type is assumed and the inversions result in size and

abundance of that type of scatterer. For microstructure, the inversions allow the dissipation rate of turbulent kinetic energy and temperature variance to be deduced (Lavery et al., 2010a,b). For both these types of inversions the results are consistent with the direct sampling techniques, though high noise levels on thc two highest frequency channels only allowed high values of dissipation rates of turbulent kinetic energy to be inferred. However, these results strongly suggest that the existing scattering models for homogeneous and isotropic turbulence are adequate to describe the scattering.

*Scattering and turbulence anisotropy:* By comparing broadband acoustic scattering spectra measured in horizontal and vertical mode, it has been possible to assess the importance of anisotropy on scattering during the passage of non-linear internal waves on the New Jersey continental shelf. This work was performed in collaboration with Doris Leong, an M.Sc. student at Dalhousie University. The overall scattering shows statistical patterns in spectral shape that suggests anisotropy occurs in either the biology or microstructure, though there was insufficient bandwidth and/or groundtruthing to determine which. However, turbulence dissipation rates inferred from acoustic inversions of spectra yield no clear evidence of small-scale turbulence anisotropy (Leong, 2009; 2012).

*Pycnocline scattering model*: Elevated scattering at the depth of the pycnocline was often observed, even before the arrival of the NLIWs. The measured scattering spectra for the pycnocline typically show little frequency dependence, or were very slightly decreasing with increasing frequency. The mechanism giving rise to this scattering layer has not been unambiguously identified: It may arise from 1) larger zooplankton alone, in which the Rayleigh-to-geometric scattering transition has already occurred, 2) a "mixed" scattering mechanism, in which the contribution at lower frequencies is dominated by turbulent temperature microstructure or large zooplankton while the contribution at higher frequencies is dominated by small zooplankton, or 3) coherent scattering (reflection) from the pycnocline, that is, scattering from strong temperature and salinity gradients. A physics-based, gradient scattering model, that incorporates measured density and sound speed gradients, has been developed (Ross and Lavery, 2012) which modifies and extends a model developed by Lavery (Lavery and Ross, 2007). Predictions at select sites have been compared to the measured pycnocline scattering to help elucidate the possible scattering mechanisms. The coincident high-resolution profiles measured directly with the microstructure profiler have been used as input for the scattering model. This simple model consists of dividing the density and sound speed profiles into a finite number of sublayers, each with homogeneous density and sound speed. The upper and lower mixed layers are modeled as homogeneous half-spaces. The scattered pressure at each interface is then calculated and added coherently. The scattering from the pycnocline falls into the weak-scattering regime as the density and sound speed gradients, based on measurements of temperature and salinity, were small. However, though there are a number of locations in which the backscattering from oceanic pycnoclines is predicted to be measurable, particularly locations in which there is significant salinity gradient, the predicted scattering from the seasonal pycnocline during SW06 was not able to account for the observed scattering. It is possible that turbulence or passive tracers were contributing significantly to the scattering, though a location was chosen in which the turbulence levels measured directly were not significant, and thus turbulence was not predicted to dominate the scattering.

*Echo statistics:* The echo statistics of scattering from fish are relatively well studied (e.g. Stanton, 1985; Stanton and Clay, 1986; Stanton et al., 2004; Chu and Stanton, 2010; Stanton and Chu, 2010) and have been show to produce, for example, estimates of fish densities. The echo statistics of scattering from zooplankton are less well studied (e.g. Stanton, 1985; Stanton et al., 2004; Trevorrow and Tanaka, 1997; Trevorrow et al., 2005), though these too have resulted in estimates of zooplankton abundance (Stanton et al., 2004; Trevorrow and Tanaka, 1997; Trevorrow et al., 2005). The published studies on the echo statistics of zooplankton have focused on either relatively large individuals, such as euphausiids or amphipods (Stanton, 1985; Stanton et al., 2004; Trevorrow and Tanaka, 1997), and/or relatively rare and strong scatters, such as siphonophores (Trevorrow et al., 2005). This project has focused on echoes from relatively small zooplankton, such as pteropods or copepods, potentially in the presence of microstructure or in mixed zooplankton assemblages. The echo statistics of backscattering from turbulent oceanic microstructure has received virtually no attention, even though the echo statistics of acoustic scattering from a turbulent atmosphere has been better studied (Kallistratova, 2002).

In this study, the statistics of the echo envelope after pulse compression for microstructure and zooplankton have been investigated. Sequential pings within areas that are spectrally classified as due to turbulence alone, zooplankton alone, due to a mixture of the two, and due to noise have been investigated. In all cases the probability density function (PDF) was generally Rayleigh-like. However, in the upper mixed layer, for which there was not sufficient spectral structure (flat to slightly decreasing scattering spectrum) or ground-truthing information for the scattering mechanism to be definitively identified, the measured PDF was mildly non-Rayleigh. This supports the hypothesis that the scattering in the upper mixed layer might be due, at least in part, to larger scatterers, such as fish or larger zooplankton that have already reached the Rayleigh to geometric scattering transition.

## IMPACT/APPLICATIONS

It is important to understand the circumstance under which different processes and/or targets contribute to high-frequency acoustic scattering. For example, a common misconception is that high-frequency acoustic scattering in the water-column is dominated by biological organisms. Only recently has it become more accepted that microstructure can also contribute to scattering, under certain circumstances. Similarly there is only anecdotal evidence that the seasonal pycnocline can contribute to high-frequency acoustic backscattering. The results of the measurements performed here provide additional evidence that small-scale turbulent fluid processes can be significant contributors to volume scattering in regions of internal solitary waves. This project has also developed high-frequency broadband acoustic scattering techniques that 1) increase the circumstances under which scattering from microstructure and biology can be distinguished, and 2) increase the spatial resolution with which physical and biological processes are imaged, which is especially relevant as it has become increasingly evident that thin biological and physical layers are prevalent in coastal regions.

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**STUDENTS ASSOCIATED TO THIS PROJECT**

Wu-Jung Lee, Ph.D. Student, WHOI/MIT Joint Program. Echo Statistics. Doris Leong, M.Sc. Student, Dalhousie University, Canada. Turbulence Anisotropy. Paul Heslinga, WHOI Guest Summer Student, Cruise Participation.

## HONORS/AWARDS/PRIZES

Lavery, A.C. was awarded a WHOI Coastal Ocean Institute Fellowship from 2006-2009.
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